Envelopce-Tracking Power Supply Reference Design for Audio Power Amplifiers with TPS61088

Designs Overview
This reference design delivers an envelope-tracking power supply circuit for audio power amplifier (PA) with TPS61088. By adding an audio envelope signal to the FB pin, the TPS61088’s output voltage can change in accordance with the envelope of the audio signal. So the TPS61088 provides a dynamically changing supply voltage to the PA. Thus the PA can always keep high efficiency in the whole output power range.

Design Features
- Input voltage range: 2.7-4.2V
- Output voltage range: 5.5-11.75V
- The output voltage changes linearly with the amplitude of the audio signal
- The output voltage rise up from 5.5V to 11.75V within 1ms under a full range step up of the audio signal
- The PA can always operate at high-efficiency in the whole output power range

Design Resources
- PMP9774
- TPS61088
- OPA4377
- All Design files
- Product Folder
- Product Folder

An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

TINA-TI is a trademark of Texas Instruments
WEBENCH is a registered trademark of Texas Instruments
1 Introduction

The traditional fixed power supply audio PA has been well established for many years. The shortage of this fixed power supply PA is that when the input audio signal’s peak to average ratio is high, the conversion efficiency will be low. Because during the periods of the peaks, the PA requires a full voltage to be able to deliver the required power without running into distortion, but during the periods of lower signal amplitude, this full voltage is not required and keeping high power supply voltage means unnecessary power is dissipated.

Figure 1. Audio Signal with High Peak to Average Ratio

This reference design delivers an envelope-tracking power supply circuit for the PA with TPS61088. The objective of envelope-tracking is to improve the efficiency of PA in the full range of the output power. By adding an audio envelope signal to the FB pin, the TPS61088’s output voltage can change in accordance with the envelope of the audio signal. Thus the PA can always operate at high-efficiency in the whole output power range.
2 Design Process

2.1 Specification

This reference design makes the output voltage change linearly with the amplitude of the input audio signal. The following table gives the detailed output voltages corresponding to different amplitude of the input audio signal.

### Table 1. Performance Specification

<table>
<thead>
<tr>
<th>Audio Signal _ peak(mV)</th>
<th>Output Voltage(V) (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.50</td>
</tr>
<tr>
<td>50</td>
<td>6.54</td>
</tr>
<tr>
<td>100</td>
<td>7.58</td>
</tr>
<tr>
<td>150</td>
<td>8.63</td>
</tr>
<tr>
<td>200</td>
<td>9.67</td>
</tr>
<tr>
<td>250</td>
<td>10.71</td>
</tr>
<tr>
<td>300</td>
<td>11.75</td>
</tr>
</tbody>
</table>

2.2 Reference Design Schematic

![Schematic of the Reference Design](image)

Figure 2. Schematic of the Reference Design
2.3 Output Voltage Setting

In this reference design, during the theoretical calculation, we set the minimum output voltage \( V_{o(min)} \) to 5.5V, set the maximum output voltage \( V_{o(max)} \) to 11.75V.

Refer to the schematic in Figure.2, when the input audio signal is 0V, the output of the envelope-tracking circuit is 0V. So the current flowing through Q1 is 0A. In this case, the output voltage \( V_{o(min)} \) is determined by \( R_0, R_1, R_2 \) and the TPS61088's feedback regulation voltage \( V_{FB} \). We put two resistors (\( R_0 \) and \( R_1 \)) at the high side of the output voltage dividing network to make the resistors selection more flexible.

From the TPS61088’s datasheet, we know that the FB pin’s maximum leakage current is 100nA. So the current through the resistance divider should be higher than 20μA to ensure the output voltage precision. A standard low side resistor \( R_2 \) of 57.6kΩ is selected. The high side resistors \( R_0 \) and \( R_1 \) can be calculated from the following equation:

\[
\frac{V_{o(min)} - V_{FB}}{R_0 + R_1} = \frac{V_{FB}}{R_2} \quad (1)
\]

Where

- \( V_{FB} \) is the TPS61088’s feedback regulation voltage (\( V_{FB} = 1.204V \)).

So the total value of \( R_0 \) and \( R_1 \) is 205.5kΩ. Here, we choose \( R_0 = 499Ω, R_1 = 205kΩ \).

When the input audio signal is at its maximum amplitude of 300 mV, the output voltage of the envelope-tracking circuit is 600mV. The current flowing through Q1 reaches its maximum value. The TPS61088’s output voltage also reaches its maximum value. The maximum current flowing through Q1 (\( I_{Q1(max)} \)) can be calculated as:

\[
I_{Q1(max)} = \frac{(V_{o(max)} - V_{FB})}{R_0 + R_1} = \frac{V_{FB}}{R_2} = 30.42μA \quad (2)
\]

The resistors \( R_{18} \) can be calculated by the following equation:

\[
R_{18} = \frac{V_{envelop(max)}}{I_{Q1(max)}} \approx 19.6kΩ \quad (3)
\]

Here we choose \( R_{19} = 10kΩ \).

Where

- \( V_{envelop(max)} = 600mV \) (two times of the maximum amplitude of the input audio signal).

2.4 Switching Frequency Setting

The TPS61088’s switching frequency is set by the resistor \( R_3 \) which is connected between the FSW pin and the SW pin. This resistor can be calculated by the following equation:

\[
R_3 = \frac{4 \cdot \left( \frac{1}{f_{sw}} - t_{DELAY} \cdot \frac{V_{o(max)}}{V_{in}} \right)}{C_{FREQ}} \approx 255kΩ \quad (4)
\]

Where

- \( f_{sw} \) is the desired switching frequency (\( f_{sw} = 600kHz \)).
- \( t_{DELAY} = 89 \) ns.
- \( C_{FREQ} = 23 \) pF.
- $V_{in}$ is the input voltage.

2.5 Peak Current Limit Setting

The peak switch current limit is set by the external resistor R4 (Figure 2). We should make sure that the current limit point is higher than the required peak switch current at the lowest input voltage and highest output power condition. The current limit value under PFM mode can be calculated by the following equation:

$$I_{LIM} = \frac{1190000}{R4} = 13.1A$$  \hspace{1cm} (5)

Where

- R4 is the resistance connected between the I_LIM pin and ground (R9=90.9KΩ).
- I_LIM is the peak switch current limit.

When the audio signal steps from 0V to 300mV, the TPS61088’s output voltage will rise from 5.5V to 11.75V. In order to make the TPS61088’s output voltage rise up quickly during this transition, we choose $I_{LIM}=13.1A$, which is 2.8A higher than the peak switch current (the peak switch current is 10.23A by equation 6). Higher current limit point means the output capacitor can be charged up more quickly, which also means the output voltage can rise up more quickly. But if we set the current limit value to an even higher point, the TPS61088 will have thermal issue.

If the MODE pin is short to ground, the current limit value is 1.6A lower than that of floating the MODE pin. We need to change R4 to 82.5k to ensure the current limit point is unchanged.

2.6 Inductor Selection

The inductor L1 is the most important component in the switching power supply design. Because it can affect the power supplier’s steady state operation, transient behavior, loop stability, and the conversion efficiency.

One of the main parameter of the inductor is the saturation current. The saturation current of the selected inductor should be higher than the peak switching current at the maximum output power condition. Suppose the conversion efficiency $\eta=0.88$ at the minimum input voltage condition, then the maximum input current is:

$$I_{in(max)} = \frac{V_{o(max)} \cdot V_{o(max)}}{R_{load} \cdot V_{in(min)} \cdot \eta} = 8.72A$$  \hspace{1cm} (6)

Set the inductor L1’s ripple current to about 35% of the average inductor current (input current). Then the peak switching current is:

$$I_{in(peak)} = I_{in(max)} + I_{in(max)} \cdot \frac{0.35}{2} = 10.23A$$  \hspace{1cm} (7)

As the current limit point (13.1A) is much higher than the peak switch current. The inductor L1’s saturation current should be higher than the current limit point instead of the peak switch current.

Another main parameter of the inductor is the inductor value. The inductor value can be calculated by the following equation:
\[ L1 = \left( \frac{V_{in(min)}}{V_{o(max)}} \right)^2 \cdot \left( \frac{V_{o(max)} - V_{in(min)}}{V_{o(max)} \cdot R_{load} \cdot f_{sw}} \right) \cdot \left( \eta \frac{0.35}{\eta} \right) \approx 1.2 \mu H \] (8)

Where

- \( R_{load} \) is the output load resistance (\( R_{load} = 6 \Omega \)).
- \( V_{in(min)} \) is the minimum input voltage (\( V_{in(min)} = 3V \)).

The inductor’s ripple current can be calculated by the following equation:

\[ \Delta I_{L1_{pp}} = \frac{V_{in(min)} \cdot (V_{o(max)} - V_{in(min)})}{L_1 \cdot f_{sw} \cdot V_{o(max)}} = 3.2 A \] (9)

The inductor L1’s DCR is also a key factor during the inductor selection. DCR should be as low as possible to minimize the power loss.

Finally, make sure the selected inductor type is fit for the high frequency application. At switching frequencies of 600 kHz, the inductor core loss, the proximity effect and the skin effect become very important.

### 2.7 Output Capacitor Selection

The output capacitors \( C2, C3, C4 \) and \( C5 \) can be calculated with the following equation:

\[ C_{out} = \frac{V_{o(max)} - V_{in(min)}}{V_{o(max)} \cdot f_{sw} \cdot R_{load} \cdot \Delta V_o} \] (10)

Where

- \( \Delta V_o \) is the required output voltage ripple.

Considering the capacitance derating under certain DC bias, four 22-\( \mu F \) ceramic capacitors in parallel is fit for the \( \Delta V_o=50mV \) application.

In some of the audio applications, electrolytic capacitors will be used as the decoupling capacitors between the power supply and the PA. So in order to match those applications, we add an extra 220\( \mu F \) electrolytic capacitor at the output side.

### 2.8 Compensation Circuit

The higher the cross over frequency \( f_c \), the faster the loop response is. In order to make the output voltage rise up as quickly as possible when the audio signal step up from its minimum value to its maximum value, we need to choose a high cross over frequency \( f_c \) while keeping the loop stability at the same time. The cross over frequency at low output voltage condition is wider than that of the high output voltage condition. So we choose \( f_c=30kHz \) when \( V_{o(min)}=5.5V \).

The COMP pin is the output of the internal trans-conductance error amplifier. The following equation can be used to calculate \( R5 \) (Rcomp) and \( C8 \) (Ccomp) (Figure 3).

\[ R5 = \frac{2\pi \cdot V_{o(min)} \cdot R_{sense} \cdot f_c \cdot C_{out}}{(1-D) \cdot V_{FB} \cdot G_{EA}} \] (11)
\[ C_8 = \frac{R_{load} \cdot C_{out}}{2 \cdot R_5} \quad (12) \]

Where:
- \( R_{sense} \) is the equivalent internal current sense resistor, which is 0.08 \( \Omega \).
- \( D \) is the switching duty cycle under \( V_{in} = 4.2V \) and \( V_{o(min)} = 5.5V \).
- \( C_{out} \) is the output capacitance (effective \( C_{out} \approx 250 \mu F \)).
- \( G_{EA} \) is the error amplifier’s trans-conductance (\( G_{EA} = 190 \mu A/V \)).

\( R_5 = 121k \) and \( C_8 = 6.8nF \) are used in this reference design.

The value of \( C_7 \) can be calculated by the equation 13:
\[ C_7 = \frac{R_{ESR} \cdot C_{out}}{R_5} \quad (13) \]

We use four 22-\( \mu \)F ceramic capacitors and one 220\( \mu \)F electrolytic capacitor at the output side. The equivalent ESR of the output capacitor is very small, about 50m\( \Omega \). So we choose \( C_7 = 100pF \) to compensate the ESR zero.
3 PCB Layout

This reference design is implemented on a 2-layer PCB. All the components are placed on the top layer. Figure 3 shows the top layer and top silk screen. Figure 4 shows the layout of the bottom layer.
4 Test Result

Figure 5 shows the output voltage versus the amplitude of the input audio signal.

![Graph showing the output voltage versus audio signal amplitude](image)

Figure 5 Vo VS. Audio Signal

Figure 6.1, Figure 6.2, Figure 6.3 and Figure 6.4 show the transition of the output voltage rise up from $V_{o(min)}$ to $V_{o(max)}$ when the input audio signal steps up from 0mV to 300mV ($V_{in}=3.6V$, $R_{load}=6$ ohm).

![Figure 6.1 Output Voltage Transition at $f_{audio}=20$kHz](image)

![Figure 6.2 Output Voltage Transition at $f_{audio}=1$kHz](image)

![Figure 6.3 Output Voltage Transition at $f_{audio}=100$Hz](image)

![Figure 6.4 Output Voltage Transition at $f_{audio}=20$Hz](image)
Figure 7.1 and Figure 7.2 show the inductor L1’s current, TPS61088’s SW pin voltage and the output voltage ripple when the peak amplitude of the input audio signal is 0V and 300mV respectively ($f_{\text{audio}}=1$ KHz).

Figure 8.1 and Figure 8.2 show the start-up waveform of the inductor current, SW voltage and the output voltage when the peak amplitude of the input audio signal is 0V and 300mV respectively ($f_{\text{audio}}=1$ KHz).
Figure 9.1 and Figure 9.2 show the load transient response of the output voltage.

![Figure 9.1 Load Transient (V_{audio}=0V)](image)

![Figure 9.2 Load Transient (V_{audio}=300mV)](image)

Figure 10.1 shows the loop bode plot when the input audio signal is 0V (V_{o(min)}=5.6V).

![Figure 10.1 Loop Bode Plot (V_{l}=3.6V, R_{load}=6 ohm)](image)

Figure 10.2 shows the loop bode plot when the peak amplitude of the input audio signal is 300mV (V_{o(max)}=11.8V).

![Figure 10.2 Loop Bode Plot (V_{l}=3.6V, R_{load}=6 ohm)](image)
5 Further Discussion

In this reference design, the peak-amplitude detection circuit and the envelope-tracking circuit is realized by OPA4377. This is a rail-to-rail output (the output swing from rail is smaller than 40mV in the full temperature range), good small signal response and low cost operational amplifier.

Some low-cost amplifiers, like LM324 and LM2902, are not fit for this application. Because when the input audio signal's frequency is above 5kHz, the output waveform of the peak-amplitude detection circuit is getting distortion.

Another low cost amplifier, LMV324 is also an option for this application. But its output swing low voltage is 180mV, which is pretty high. In order to make LMV324 fit for this application, we do some modification on the schematic. A pre-biased voltage is added to the output of the envelope detection circuit.

![Figure 11. Schematic of the Reference Design with LMV324](image-url)
With the new schematic (Fig.11), when the output voltage of the envelope detection circuit is below 200mV (the input audio signal is lower than 100mV), the output voltage of TPS61088 is clamped at 6V. When the input audio signal is higher than 100mV, the output voltage of TPS61088 will increase linearly with the increment of the audio signal.

**Table 2. Performance Specification with LMV324**

<table>
<thead>
<tr>
<th>Audio Signal _ peak(mV)</th>
<th>Output Voltage(V) (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100</td>
<td>6.00</td>
</tr>
<tr>
<td>150</td>
<td>7.45</td>
</tr>
<tr>
<td>200</td>
<td>8.90</td>
</tr>
<tr>
<td>250</td>
<td>10.35</td>
</tr>
<tr>
<td>300</td>
<td>11.80</td>
</tr>
</tbody>
</table>
IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated (“TI”) reference designs are solely intended to assist designers (“Buyers”) who are developing systems that incorporate TI semiconductor products (also referred to herein as “components”). Buyer understands and agrees that Buyer remains responsible for using its independent analysis, evaluation and judgment in designing Buyer’s systems and products.

TI reference designs have been created using standard laboratory conditions and engineering practices. TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design. TI may make corrections, enhancements, improvements and other changes to its reference designs.

Buyers are authorized to use TI reference designs with the TI component(s) identified in each particular reference design and to modify the reference design in the development of their end products. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY THIRD PARTY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT, IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used.

Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS ARE PROVIDED “AS IS”. TI MAKES NO WARRANTIES OR REPRESENTATIONS WITH REGARD TO THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, EXPRESS, IMPLIED OR STATUTORY, INCLUDING ACCURACY OR COMPLETENESS. TI DISCLAIMS ANY WARRANTY OF TITLE AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, QUIET ENJOYMENT, QUIET POSSESSION, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS WITH REGARD TO TI REFERENCE DESIGNS OR USE THEREOF. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY BUYERS AGAINST ANY THIRD PARTY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON A COMBINATION OF COMPONENTS PROVIDED IN A TI REFERENCE DESIGN. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, SPECIAL, INCIDENTAL, CONSEQUENTIAL OR INDIRECT DAMAGES, HOWEVER CAUSED, ON ANY THEORY OF LIABILITY AND WHETHER OR NOT TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, ARISING IN ANY WAY OUT OF TI REFERENCE DESIGNS OR BUYER’S USE OF TI REFERENCE DESIGNS.

TI reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques for TI components are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

Reproduction of significant portions of TI information in TI data books, data sheets or reference designs is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards that anticipate dangerous failures, monitor failures and their consequences, lessen the likelihood of dangerous failures and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in Buyer’s safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed an agreement specifically governing such use.

Only those TI components that have specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have not been so designated is solely at Buyer’s risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.